MEASURED AND CALCULATED CHARACTERISTICS OF WIND TURBINE NOISE

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ABSTRACT

This paper presents the results of an analytical and experimental investigation of wind turbine noise. Noise calculations indicate that for configurations with the rotor downwind of the support tower, the primary source of noise is the rapid change in rotor loading which occurs as the rotor passes through the tower wake. Noise measurements are presented for solid and truss-type tower models with both upwind and downwind rotors. Upwind rotor configurations are shown to be significantly quieter than downwind configurations. The model data suggest that averaged noise measurements and noise calculations based on averaged tower wake characteristics may not accurately represent the impulsive noise characteristics of downwind rotor configurations.

INTRODUCTION

One of the desirable characteristics of wind turbines is their minimal effect on the environment when compared to other methods of power generation. In particular, there is little evidence to suggest that wind turbines should be noisy. For example, reference 1 presented detailed noise measurements to show that the acoustic impact of a 38m (125 ft.) diameter, 100 kw wind turbine is minimal.

However, the noise resulting from the operation of a recently constructed 61m (200 ft.) diameter, 2000 kw wind turbine at Boone, North Carolina has caused concern for the community noise impact of very large wind turbines. The Boone wind turbine, designated the MOD-1, has caused nearby residents to complain of a periodic thumping sound. Noise calculations presented in reference 2 showed that for wind turbines such as the MOD-1 which have rotors downwind of their support towers, the dominant noise source can be the rapid change in rotor loading which occurs when the rotor passes through the tower wake. Because of the severity of the MOD-1 noise problem, an analytical and experimental investigation was conducted to identify promising noise control methods. The purpose of this paper is to present the results of that investigation and to provide some guidelines for designing wind turbines using both solid and truss-type towers.

NOISE CALCULATIONS

The noise calculations described herein were made using the technique described in reference 3. This is a "first principles" noise prediction technique which requires as input the detailed load distribution of the rotor as a function of time. It has been shown to give excellent results for propeller configurations where the blade loading is accurately known. Therefore, the principal difficulty in accurately calculating wind turbine noise is defining the rotor loading as it passes through the tower wake.

There are several options available for estimating rotor loadings for input to the noise calculations. One is to use wind tunnel measurements of tower wake characteristics such as those presented in reference 4. These are average wake characteristics and can be used to calculate average noise characteristics. Several researchers have made noise calculations using these wake characteristics and have obtained reasonably good agreement with average noise measurements on the MOD-1 wind turbine.

There has been no attempt to estimate the transient wake characteristics and rotor loadings which might be used for a more accurate noise prediction, and with good reason. As can be appreciated from figure 1, the MOD-1 rotor operates in a very complex wake which must vary considerably with wind speed (Reynolds number) and wind direction.

In addition, the wind turbine is situated in a small clearing surrounded by deciduous trees. The treetops, which can be seen in figure 1, are approximately the same height as the bottom of the rotor disk. Therefore, there can be a significant seasonal change in the turbine noise noise resulting from the change in the thickness of the atmospheric boundary layer. When the trees lose their leaves, the wind speed through the tower can be higher and therefore the rotor can experience a greater change in loading as it passes behind the tower.

Because of the complexity of the wake and since there were no rotor load measurements on the MOD-1 machine, initial calculations to understand noise mechanisms were made using very simplistic models of the rotor loading as it passed through the tower wake. Figures 2 and 3 show three assumed loading models and the corresponding time histories and spectra. The baseline case assumed no tower interference and resulted in no noise which would be visible at the scale used in figure 2. This case approximated the upwind rotor configuration. The level of the fundamental for this case is shown as the solid symbol in figure 3, all higher harmonics were insignificant.

The other two cases were single and double "notch" wake loadings to determine if the noise was due to the general existence of the wake or to the details of the wake structure. The single "notch" loading is seen to produce a single impulse time history while the double "notch" produces a double impulse as one would expect. The levels of the pressure impulses are approximately the same as are the overall noise levels. In the frequency domain it can be seen that the double "notch" loading causes the maximum noise levels to shift to a higher frequency. This results in a dramatic increase in the apparent loudness of the noise. Since the MOD-1 noise data contain multiple pulses, it was concluded that the MOD-1 noise problem was due primarily to the change in rotor loading caused by the individual tower leg wakes. It was also apparent that if the wake could be changed to produce a rotor loading more like the single notch, then the audible noise level could be reduced.

EXPLORATORY NOISE TESTS

A series of exploratory noise tests were conducted to determine if the trends which were predicted analytically could be duplicated in the wind tunnel. The cylindrical shapes shown in figure 4 were tested upwind of a model airplane propeller. Three of the cylinders were made of screens of varying porosity for comparison with a solid cylinder of the same diameter. In addition, two smaller cylinders were tested, one with a spiral strake and one plain.

Average noise spectra were generated for each of these configurations. These measurements confirmed the analytical trends in that the fine mesh and solid cylinders were significantly quieter than the more porous cylinders. A simple truss structure, shown in figure 5, was also tested. Average noise spectra were generated for both the basic tower configuration and with part of the tower taped to represent a solid surface. The taped portion of the tower was adjacent to the outer half of the rotor blade. Again, the average noise spectra indicated a significant reduction in noise.

MOD-1 MODEL TESTS

Based on the results of the exploratory tests, a model of the MOD-1 tower was constructed and tested in an anechoic wind tunnel. The overall installation in the anechoic wind tunnel is shown in figure 6(a) and a close-up of the tower is shown in figure 6(b). Tower details were carefully scaled in order to reproduce as nearly as possible the details of the tower wake. The geometric scale was 1:140 and the wind tunnel speed was 21 m/sec (70 ft/sec). This resulted in a model Reynolds number about 1/100 of the full scale value (depending on wind speed). The rotational speed of the rotor was chosen to match the model and full scale tip speeds. Because of the high rotational speeds, the model rotor had a straight blade (no coning) to minimize structural problems. The MOD-1 rotor planform and twist were modeled as closely as possible.

Because the model blade was straight, it was not possible to duplicate the rotor/tower spacing along the entire blade. The .75 radius position was chosen to match the spacing. Therefore, the outer portion of the blade operated closer to the tower than full scale and the inner portions were further away.

Noise measurements were made with a microphone located outside the wind stream at a slant distance of 1.8m (6 ft.). The microphone was downwind of the rotor plane at an angle of 56 degrees from the rotor axis and an azimuth position of 120 degrees, measured counterclockwise (facing upwind), from a zero degree position with the rotor blade tip at the base of the tower.

Figure 7 shows the average noise spectra for the MOD-1 model rotor without any flow interference other than the upstream influence of the streamlined rotor mounting strut. This represents the minimum noise level which could be achieved with the model rotor in the airstream. Since the model scale factor is 140:1, a full scale frequency of 20 Hz corresponds to a model frequency of 2800 Hz.

Figure 8 shows the average noise spectra for the MOD-1 upwind configuration with the wind perpendicular to the side of the tower. As expected, there was very little increase in noise since the upstream influence of the tower is not significant beyond a few diameters of the largest structural members.

The upwind results are quite different from the downwind configuration results shown in figure 9. The average spectra show the expected substantial increase in harmonic or rotational noise. The data, taken with the wind perpendicular to the face of the tower, are typical of the downwind data although the noise spectra varied considerably as the wind direction relative to the tower was changed. This is not surprising since the tower wake and the relative spacing of the rotor and tower change with wind direction. However, there were no wind directions where the noise levels approached the low levels experienced in the upwind configuration.

Since the exploratory tests showed a substantial difference between solid and open towers, tape was applied to the MOD-1 model to simulate a solid tower. Figure 10 shows the average noise spectra for the tower with tape applied to the portion of the tower adjacent to the outer half of the rotor. As predicted by both the analysis and the exploratory tests, the periodic or rotational noise was essentially eliminated and replaced with what appears as broadband noise above a frequency of about 2800 Hz (20 Hz full scale). Since the primary MOD-1 noise complaint was a periodic thumping rather than broadband noise, the solid tower averaged data suggested that a significant noise reduction might be possible.

TRANSIENT EFFECTS

All of the results presented thus far, both calculations and measurements, assumed that the noise problem can be characterized in an average sense. In this section we will examine that assumption in terms of model noise measurements. Before discussing the model measurements it is appropriate to describe the difference in the way people percieve low and high frequency periodic noise. It should be pointed out that this is not a well understood subject and that these comments are based only on the author's experience.

A noise spectra contains a subset of the information contained in the time history. A spectra describes the frequency content of the signal but contains no information on the impulsive or nonimpulsive nature of the signal. This is not a problem for most of the frequency range since the infinite number of time histories which can be generated from a given spectra will all sound the same, whether impulsive or not. However, for very low frequency noise, such as that generated by the MOD-1 wind turbine, the "character" of the time history can be important and, in particular, whether or not the signal is impulsive. The ear can discern each pressure impulse or thump from the MOD-1 and therefore the "character" of each thump is important. Since the pressure pulses can be influenced by random wake characteristics, they will not in general be exactly the same and therefore some thumps may sound louder than others. If the noise is averaged, the high frequency characteristics of the individual impulses tend to be lost. This may result in an underestimation of the noise actually generated.

Figure 11 shows an average noise spectra for a model configuration identical to the nominal MOD-1

configuration except that the rotor was positioned approximately four tower leg diameters further downwind. When compared with the average spectra for nominal spacing, figure 9, there does not appear to be a significant difference due to the increased spacing.

The time histories for the nominal and increased spacing are shown in figure 12. The wake structure is obviously very different for the two cases as evidenced by the complete change in character of the noise time histories. Although it is not possible to describe how these would sound if extrapolated to full scale, it seems probable that the alternating single and double pulses of the nominal spacing time history would sound different than the double pulses of the increased spacing time history or an average time history. The difference in the time histories shown in figure 12 is typical of the changes which occurred each time the tower configuration, wind direction or rotor spacing was changed. In general, it was not possible to look at the average noise spectra and estimate the character of the time history.

Another way of demonstrating the variability of the noise signal is to compare the averaged time histories. Figure 13 shows the average time histories for the taped-over or "solid" MOD-1 model at both the nominal tower/rotor spacing and with the spacing increased by approximately 2/3 of the overall tower "diameter." The rotor tachometer signal was used as a trigger to begin each signal average at the same shaft position. This technique enhances periodic signals and averages out the random components. The data in figure 13 are the result of 32 averages.

The nominal-spacing average time history shows the very consistent single pulse caused by the solid tower wake. In sharp contrast is the signal resulting from increasing the tower/rotor spacing. The time history of the impulse is highly variable and apparently random in nature since the average time history shows no periodic content.

The data in figure 13 are not typical although the same phenomena occurred for another configuration. In general, the averaged signal was still periodic with the pressure pulses being less distinct and more rounded than a single impulse. In the frequency domain this would correspond to a loss of the higher frequency portion of the signal which might significantly affect the apparent loudness of the noise. Therefore one should be very careful in interpreting averaged measurements of an unsteady low frequency noise.

12 SIDED TOWER TESTS

Tests were also conducted using the 2 cm diameter, 12 sided tower shown in figure 14. Figure 15 shows the average noise spectra for the configuration with the rotor located 2 diameters upwind of the center of the tower. The noise levels are not significantly different from the no-tower data of figure 7 or the MOD-1 upwind data of figure 8.

The average noise spectra for the downwind configuration (x/D = 2.8) is shown in figure 16. The harmonic noise falls off very rapidly compared to the MOD-1 downwind results of figure 9. These average spectra suggest that a small solid tower would not have a noise problem. However, when viewed from the time domain there is some uncertainty as to how noisy this tower might be.

Figure 17 presents a comparison of time histories for the MOD-1 and 12 sided towers with downwind rotors. Note the occurrence of multipeaked pulses in addition to the expected single-peaked pulses in the solid tower time history. It is not known whether or not these multipeaked pulses would exist for a full scale wind turbine. If they did exist, they might produce a thump about as loud as the MOD-1 thump. Since they do not occur periodically, an averaged measurement might not show their existence.

CONCLUDING REMARKS

The MOD-1 "thump" is the result of the interaction of the turbine rotor and the complex tower wake. Detailed calculations of the noise would require a detailed description of the rotor loading as it passes through the complex tower wake and would be difficult to make with certainty. However, average noise calculations using average wake characteristics are in general agreement with average noise measurements.

Calculations and model tests indicate that placing the rotor upwind of the support tower minimizes the noise risk. It is difficult to extrapolate model results for the downwind configuration to full scale since all the parameters which affect the wake affect the generated noise. The inherent unsteadiness of wake flows may produce noise which is louder than would be expected from average measurements or calculations based on average wake characteristics.

REFERENCES

1. Balombin, J. R.: An Exploratory Survey of Noise Levels Associated with a 100 kw Wind Turbine. NASA TM 81486, April 1980.

2. Greene, George C.; and Hubbard, Harvey H.: Some Calculated Effects of Non-Uniform Inflow on the Radiated Noise of a Large Wind Turbine. NASA TM 81813, May 1980.

3. Nystrom, P. A., and Farassat, F.: A Numerical Technique for Calculation of the Noise of High Speed Propellers with Advanced Blade Geometry. NASA TP 1662, 1980.

4. Savino, J. M.; and Wagner, L. H.: Wind Tunnel Measurements of the Tower Shadow on Models of the ERDA/NASA 100 kw Wind Turbine Tower. NASA TMX 73548, November 1976.

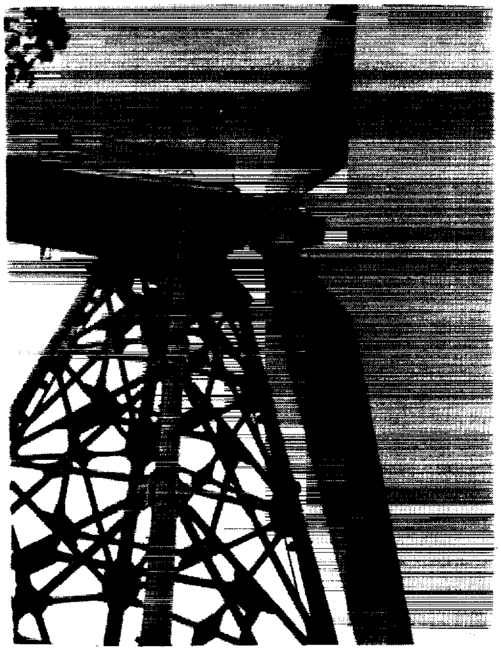

Figure 1.- DOE/NASA 2000 kw experimental wind turbine.

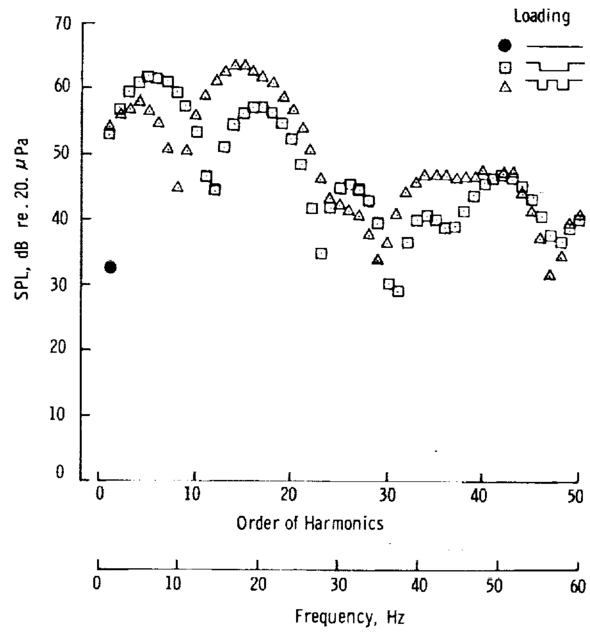

Figure 3.- Calculated noise spectra for three turbine inflow conditions.

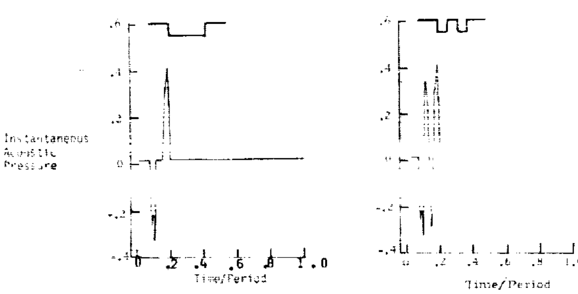

Figure 2.- Calculated noise signatures for single and double notch rotor loadings.

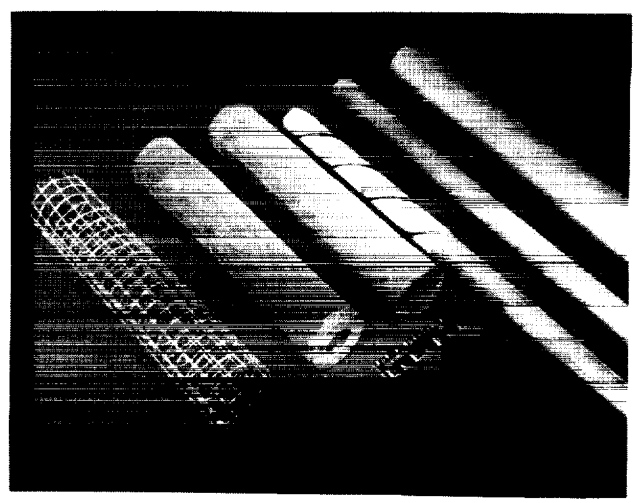

Figure 4.- Cylindrical models used in exploratory noise studies.

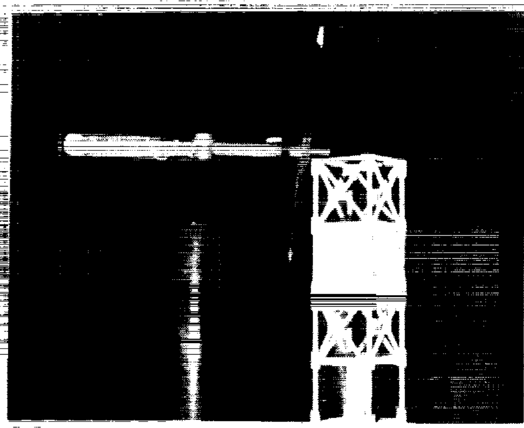

Figure 5.- Tower model (with partial tape covering) used in exploratory noise studies.

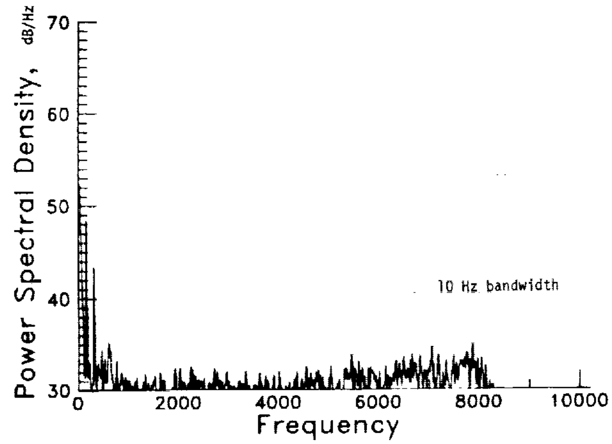

Figure 7.- Average noise spectra for MOD-1 model rotor with no support tower.

Figure 6(a).- Model installation in anechoic wind tunnel.

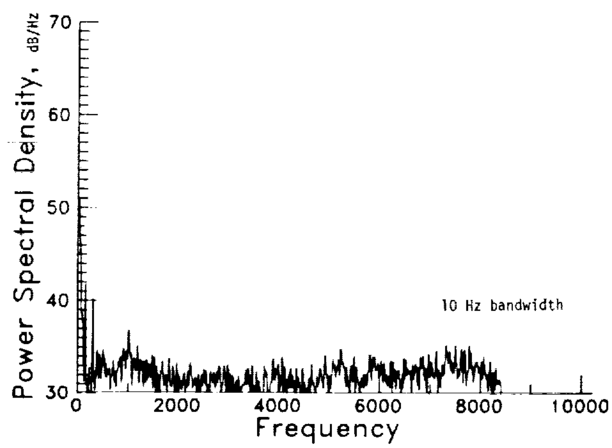

Figure 8.- Average noise spectra for MOD-1 model in the upwind configuration.

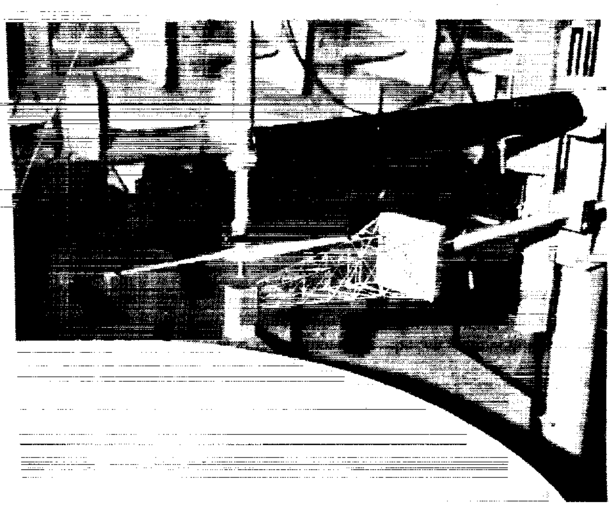

Figure 6(b).- MOD-1 tower model.

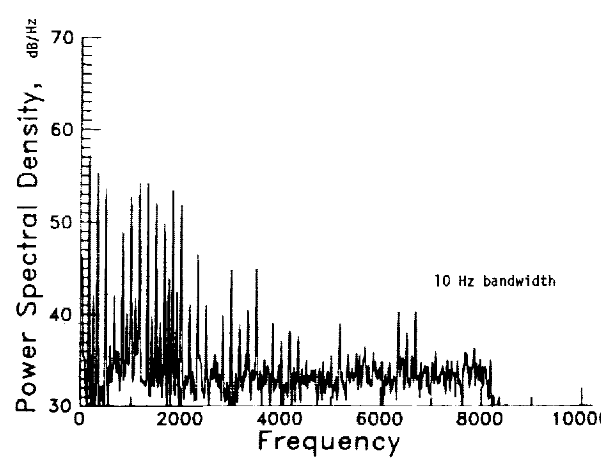

Figure 9.- Average noise spectra for MOD-1 model in the downwind configuration.

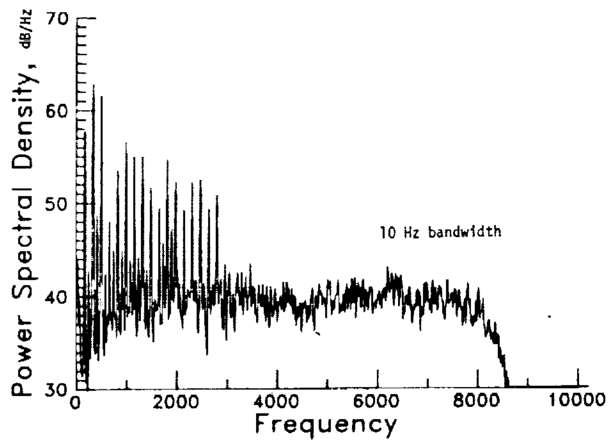

Figure 10.- Average noise spectra for MOD-1 "solid" tower model.

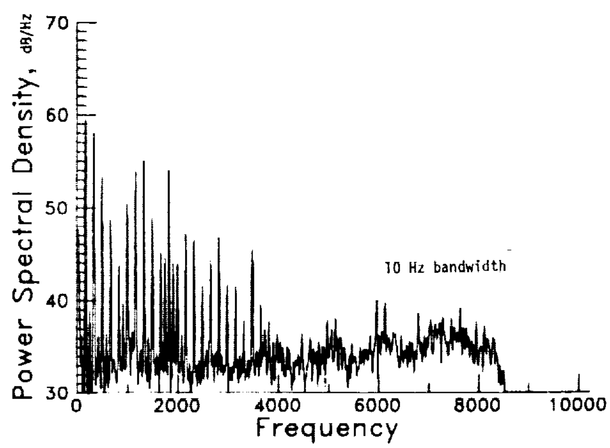

Figure 11.- Average noise spectra for MOD-1 tower model with the rotor approximately 4 tower leg diameters further downwind.

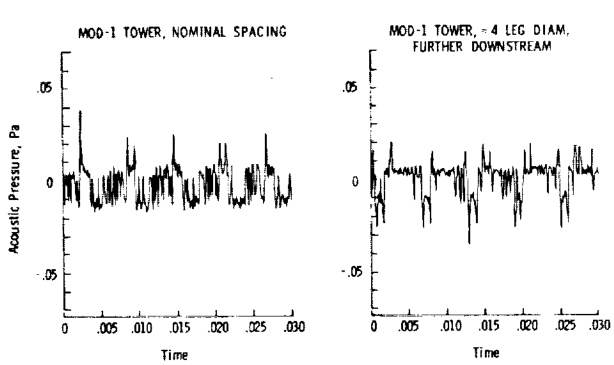

Figure 12.- Effect of tower/rotor spacing on the character of the noise time history.

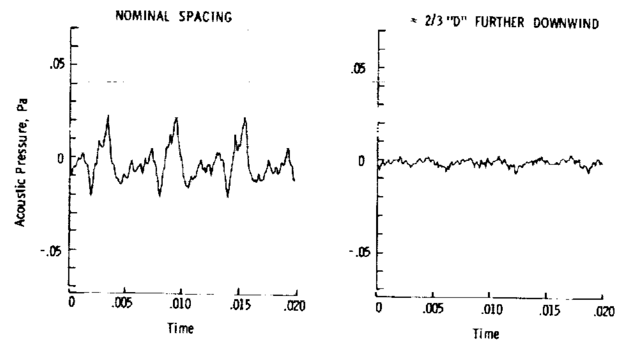

Figure 13.- Effect of tower/rotor spacing on the average time histories for the MOD-1 "solid" tower model.

Figure 14.- Twelve-sided tower installed in the anechoic wind tunnel.

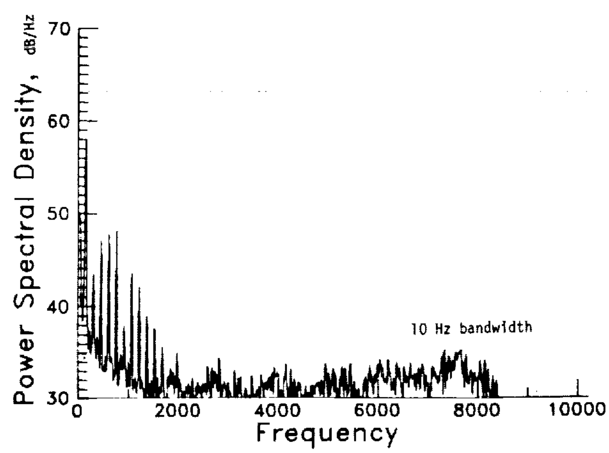

Figure 15.- Average noise spectra for the 12-sided tower model with the rotor located 2 tower diameters upwind.

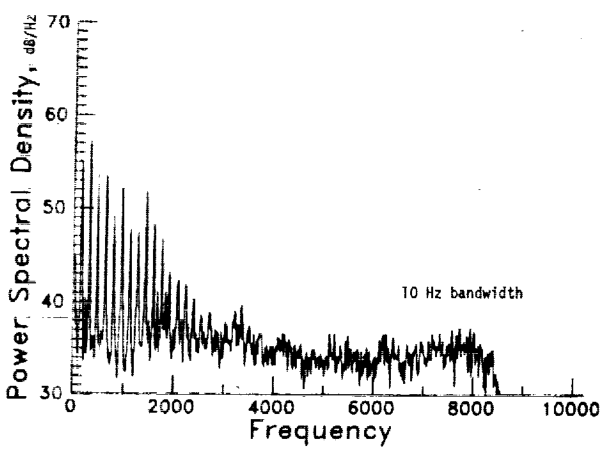

Figure 16.- Average noise spectra for the 12-sided tower with the rotor located 2.8 tower diameters downwind.

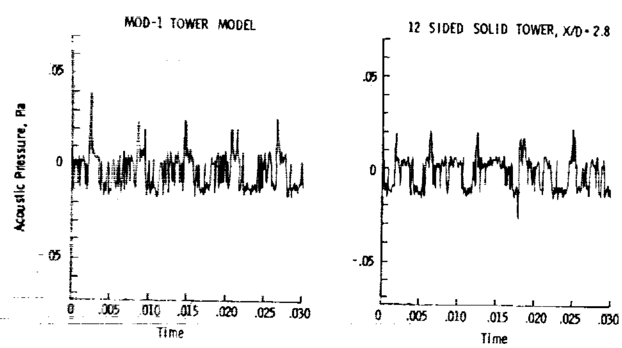

Figure 17.- Comparison of time histories for the MOD-1 and 12-sided tower models in the downwind configurations.

QUESTIONS AND ANSWERS

G. Greene

From: G.P. Tennyson

Q: Have measurements or calculations been made to determine the effects of blade planform and twist on noise? (Optimum diametrical loading should reduce shear, particularly at the blade tips and hence, noise.)

A: *Only for propeller noise, i.e., studies by OSU and MIT.*

From: R.J. Templin

Q: Did you investigate the effect of blade speed on noise, and if so, what was the effect?

A: *Did not investigate.*